# OCEAN CIRCULATION

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LECTURES

1. Introduction
2. Homogeneous model of the wind-driven circulation
3. Vertical structure of the wind-driven circulation
4. Thermohaline circulation
5. Adjustment of the large-scale circulation

REFERENCES

Both general references for further reading, and specific references cited in the lecture notes, are listed at the end of each lecture.

# 1. INTRODUCTION

Aims for today:

- Why study the oceans?
- Air-sea interaction
- Observation methods and challenges
- Overview of large-scale circulation

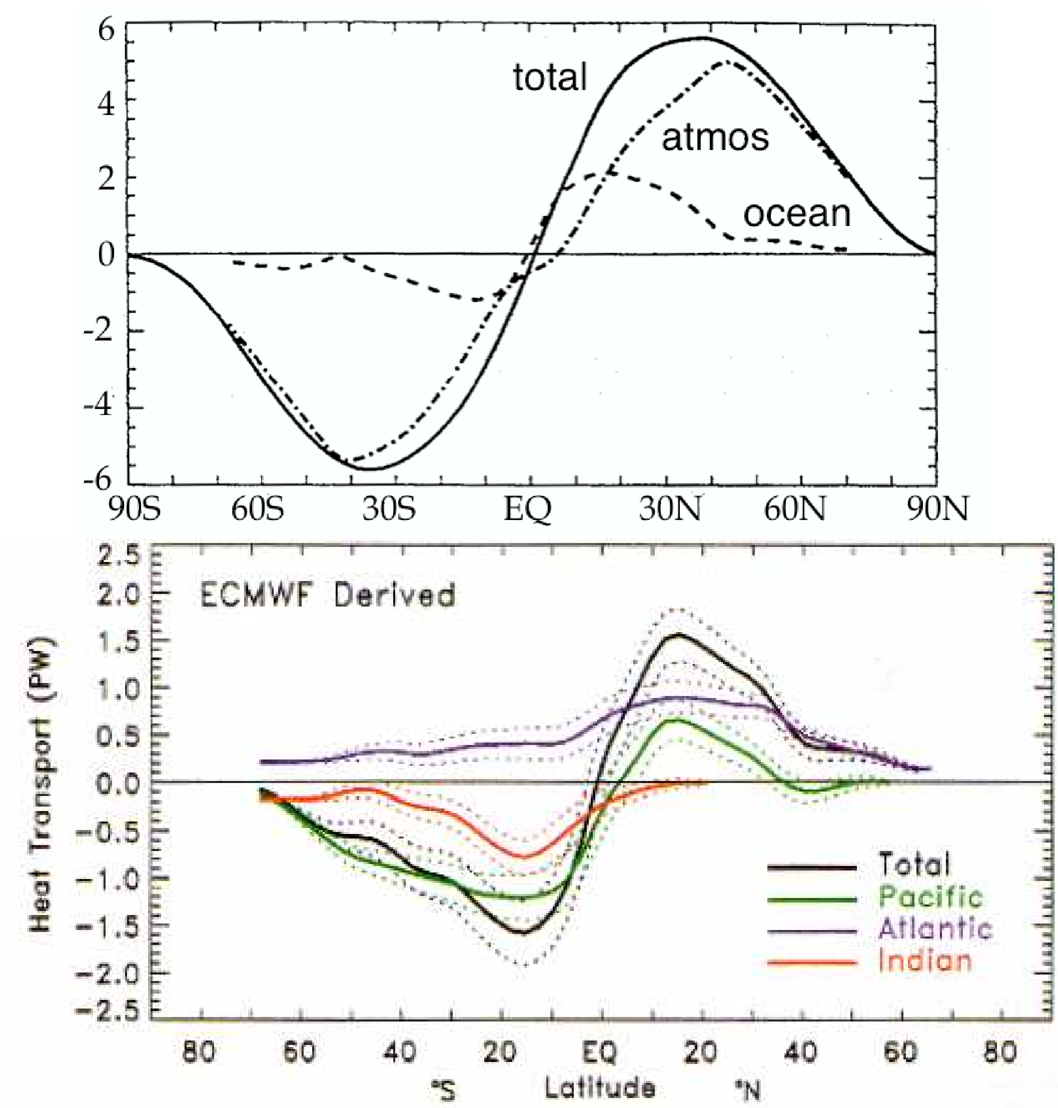
# WHY STUDY THE OCEANS?

- 71% of the Earth's surface is covered by water.
- The heat capacity of the upper 3m of the oceans is equivalent to the entire heat capacity of the atmosphere.
- The oceans transport a similar amount of heat polewards as the atmosphere.
- Changes in SST can affect the atmospheric circulation (e.g., El Niño, formation of Hurricanes)
- Long memory of oceans $\Rightarrow$ potential for seasonal climate prediction.
- The oceans store about 50 times more carbon than the atmosphere.
- The oceans take up roughly 1/3 of the carbon released into the atmosphere through human activity.
- Fisheries.
- Military.
- Mineral deposits.
- Waste disposal?
- Intellectual curiosity.

# AIR-SEA INTERACTION

The dominant source of energy for the circulations of the atmosphere and oceans is the sun.

Excess incoming-outgoing radiation at low latitudes, and vice-versa at high latitudes ⇒ the atmosphere and oceans must transport heat polewards.




(Trenberth and Caron 2001)

The oceanic circulation itself is driven by

- surface wind stresses;
- surface heat fluxes;
- freshwater fluxes (evaporation, precipitation, sea-ice formation, river discharge);
- body forces (tides).

*a. Wind stress*

Measured from ship observations (e.g., Josey et al. 2000), from operational atmospheric analyses (e.g., Trenberth et al. 1990), or from remote sensing (e.g., Liu and Katsaros 2001).

Bulk parameterisation:

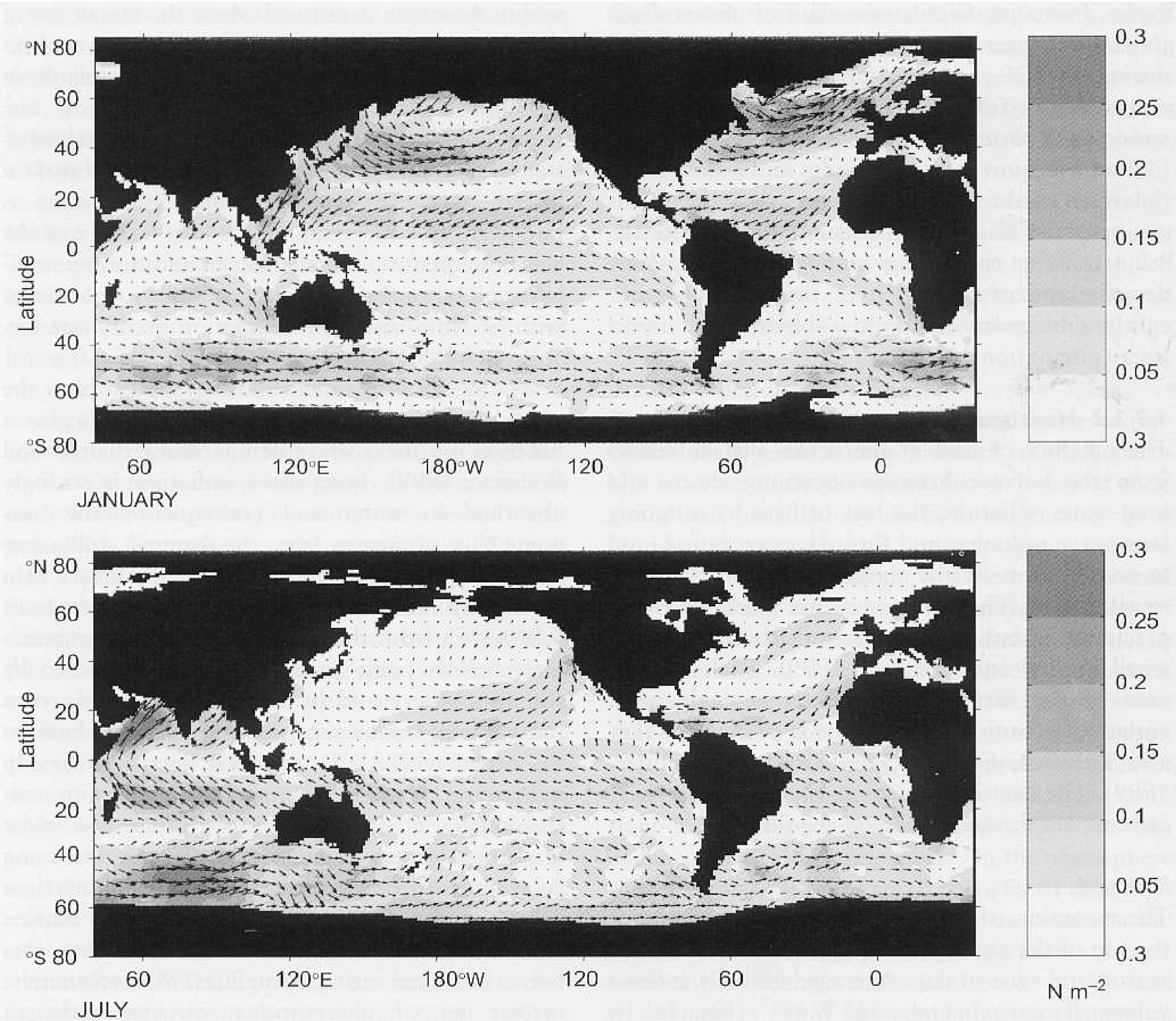
$$\tau_s = \rho_a C_D U_{10}^2, \tag{1.1}$$

where $\rho_a$ is the density of air and $U_{10}$ is the wind speed at 10 m; the drag coefficient, $C_D$, is a function of wind-speed, atmospheric stability and sea-state. Typically, use:

$$\begin{aligned} 10^3 C_D &= 1.15 && (|U_{10}| < 11\,\mathrm{m\,s^{-1}}) \\ &= 0.49 + 0.065|U_{10}| && (|U_{10}| > 11\,\mathrm{m\,s^{-1}}) \end{aligned} \tag{1.2}$$

(Large and Pond 1981)

Mean wind-stress (from Josey et al. 2000):




Note:

- wind stresses are highly variable;
- there are still significant uncertainties.

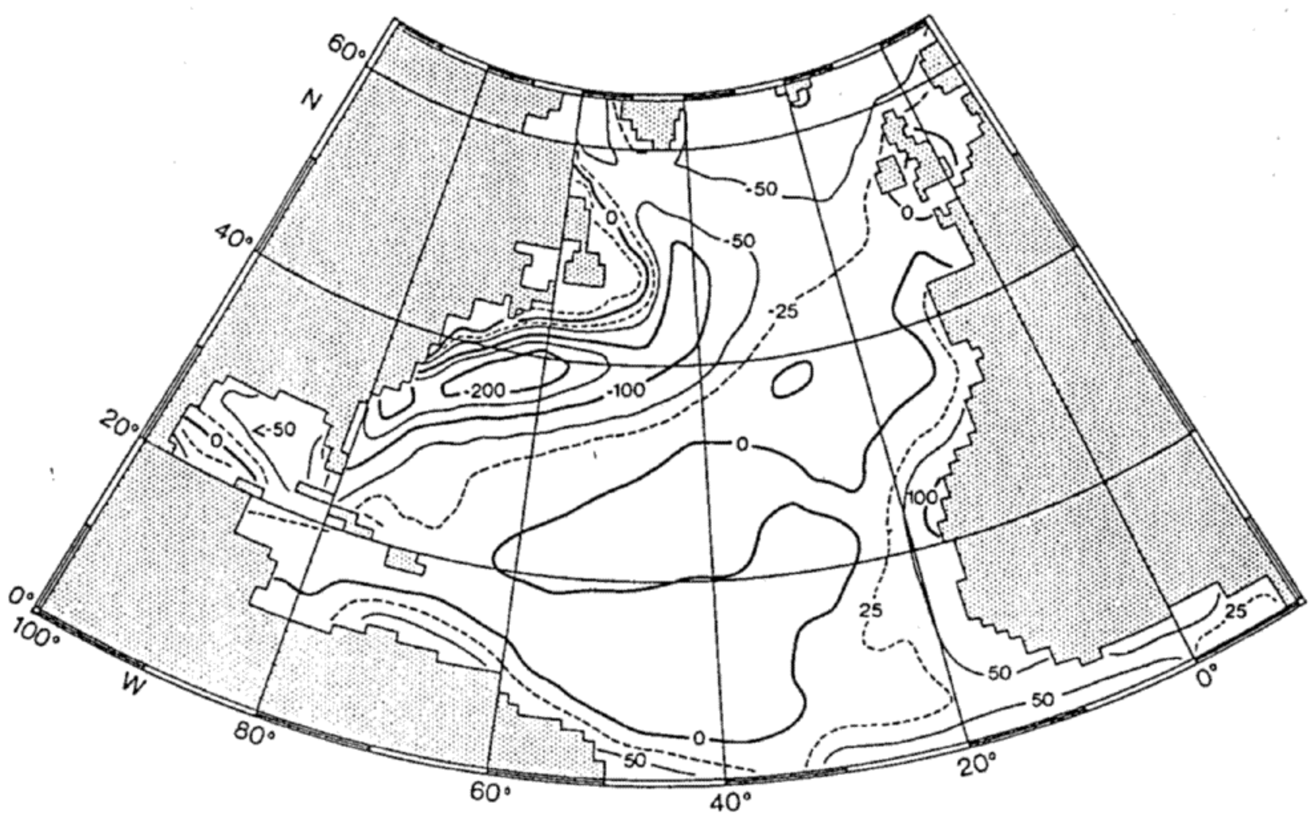
## *b. Heat flux*

Four components:

- sensible heat flux from air-sea temperature difference;
- latent heat flux associated with evaporation;
- incoming short-wave radiation from the sun;
- long-wave radiation from the atmosphere and ocean.

Again parameterised using bulk formulae (e.g., Reed 1977).

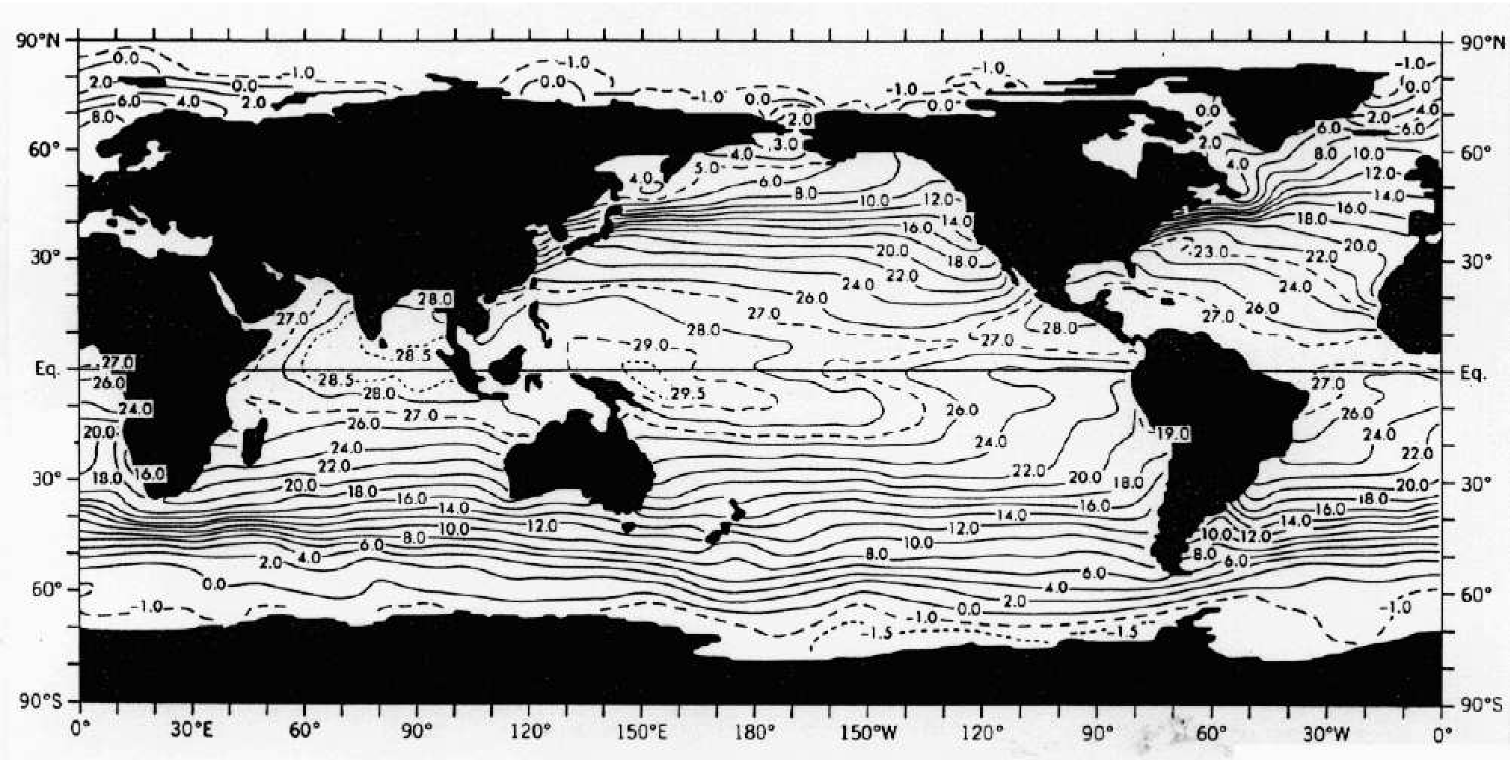
Air-sea heat flux ($W\,m^{-2}$) over the North Atlantic:




(Isemer et al. 1989)

Mean sea surface temperature

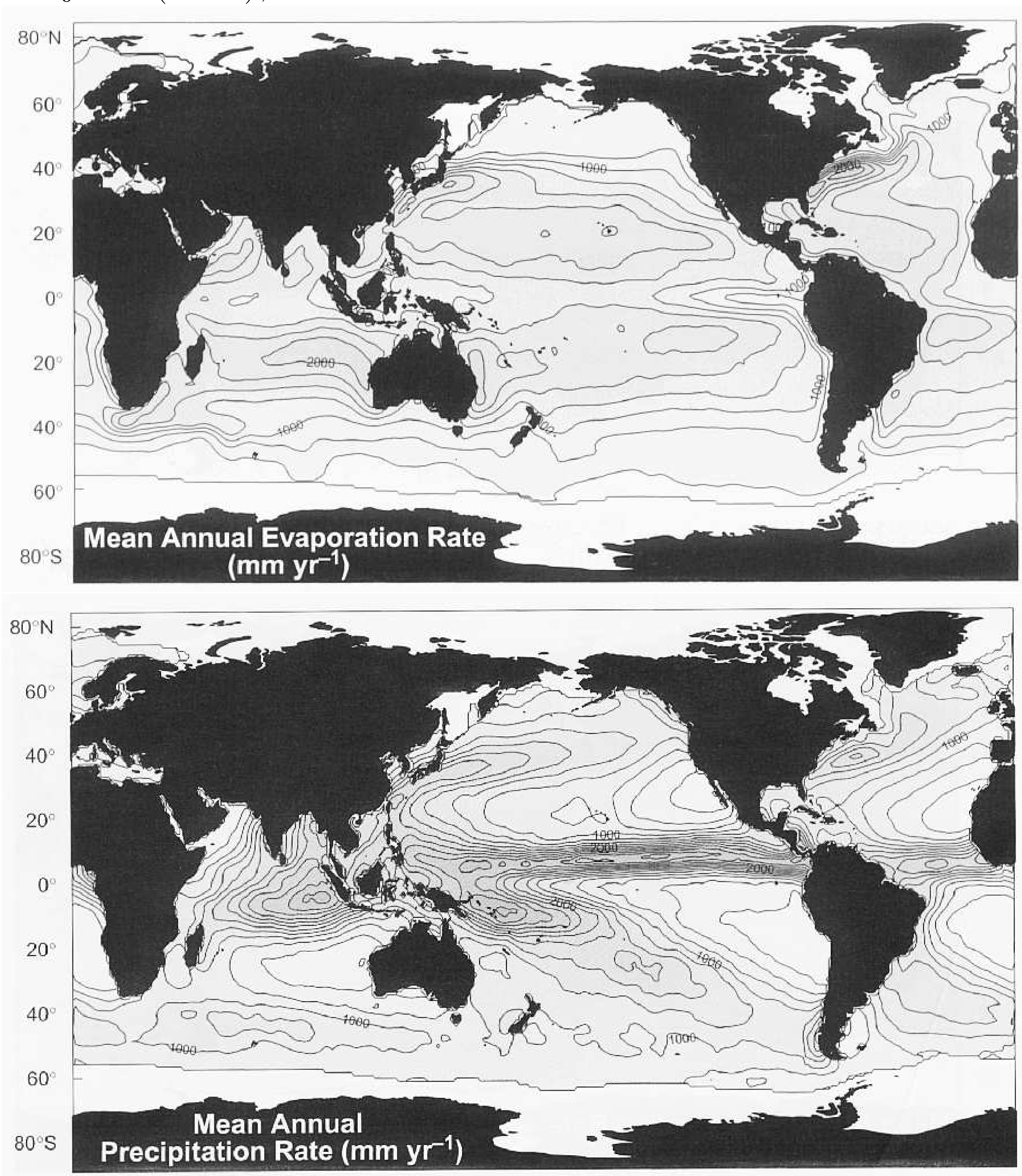
(Peixoto and Oort 1992; based on Levitus 1982):




How is this related to the net heat flux? Chicken or egg?

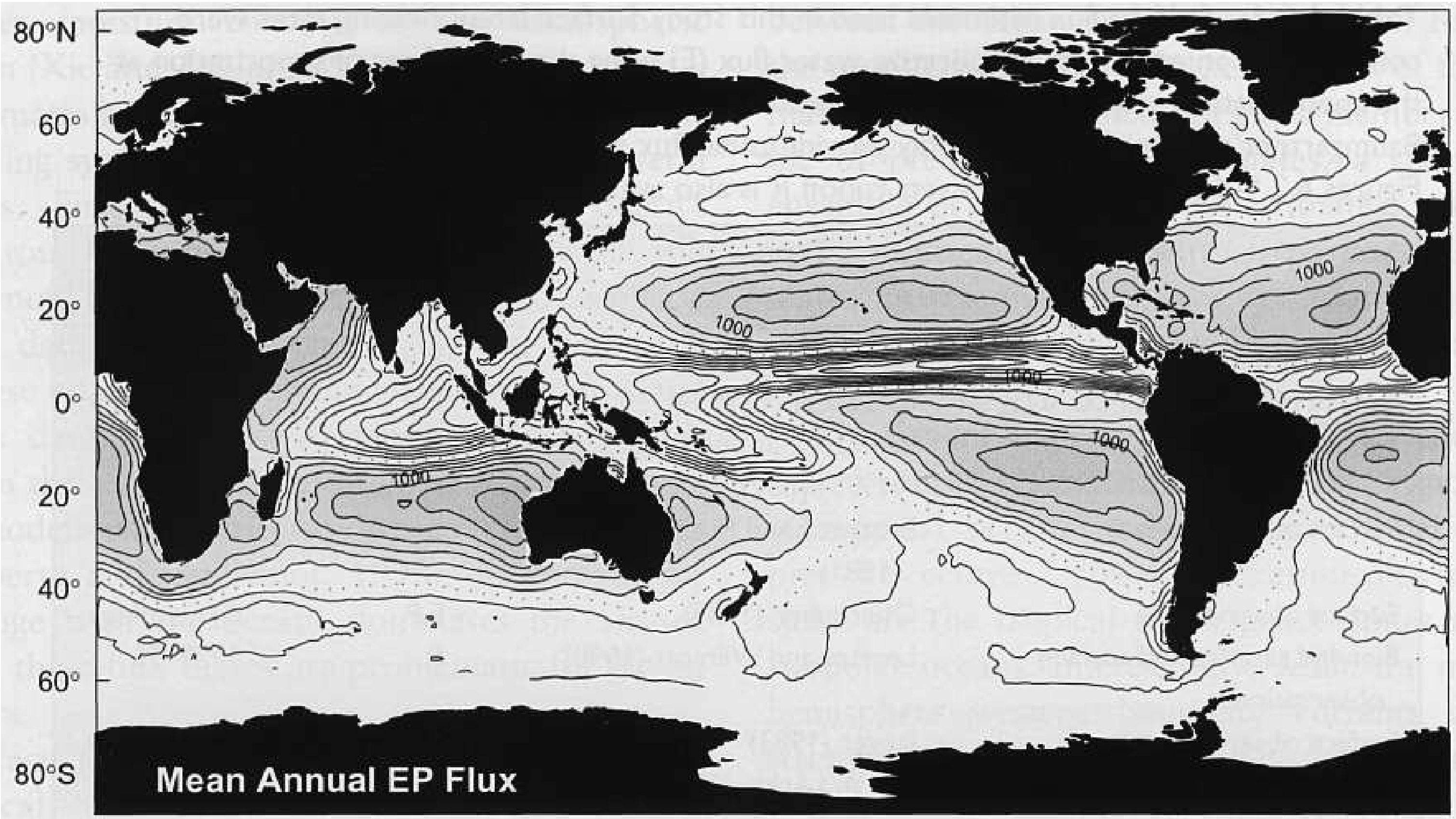
# *Freshwater flux*

Wijffels (2001), based on 13 datasets:



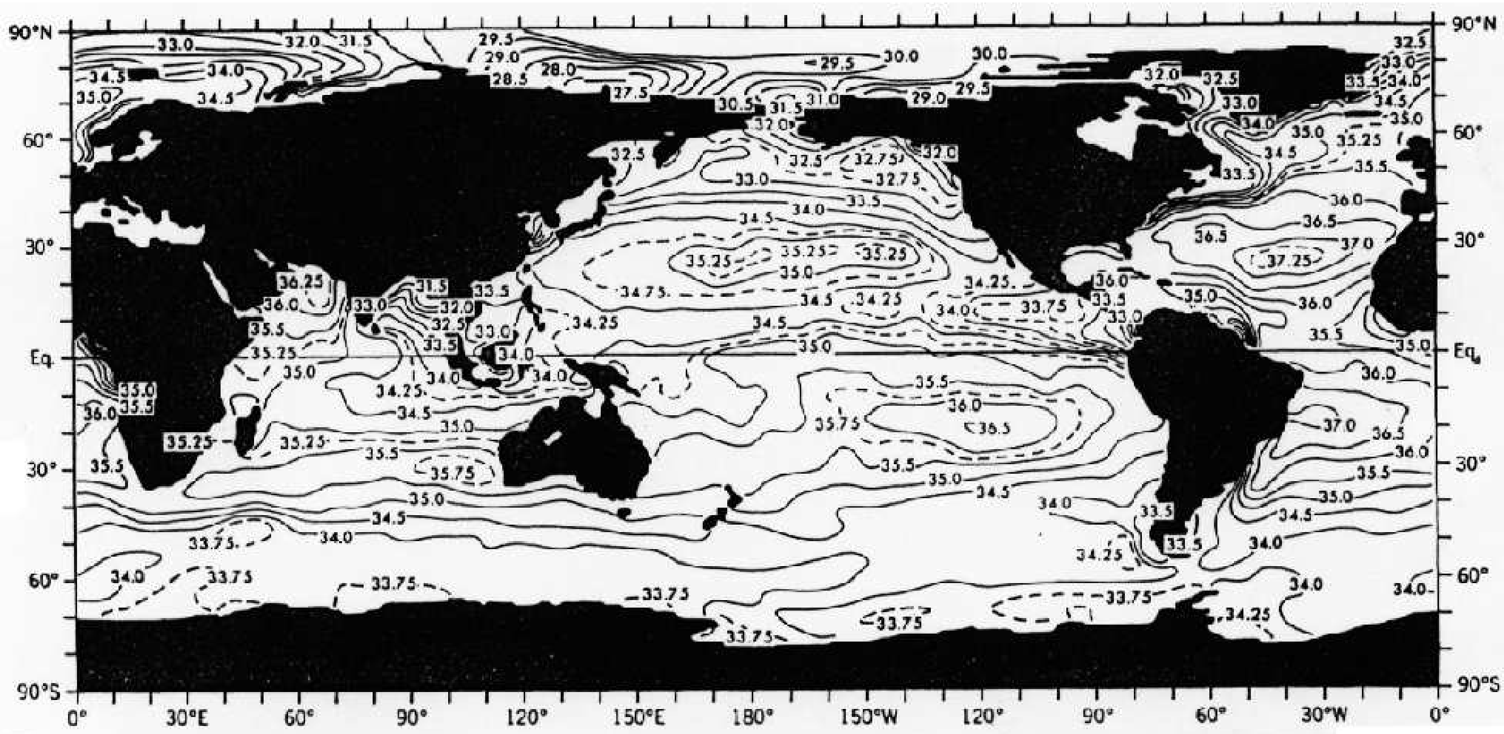

(Evaporation $\propto$ latent heat flux; $1.27\mathrm{m\,yr^{-1}} \Leftrightarrow 100\mathrm{W\,m^{-2}}$)

Net E-P flux:




(note large uncertainty: standard deviation amongst contributing datasets $\sim 250\,\mathrm{mm\,yr^{-1}}$)

Surface salinity — how is this related to E-P?




(Peixoto and Oort 1992)

# OBSERVATIONS OF LARGE-SCALE CIRCULATION

The oceans present several major observational challenges:

- remoteness and size,
- high pressures (e.g., 500 atmos. at 5km),
- highly corrosive,
- opacity to electromagnetic radiation ($\Rightarrow$ cannot "see" beneath surface),
- turbulence.

The latter is highly problematic: e.g., need $\sim 2$ weeks of continuous data to filter internal waves and measure a geostrophic current (Wunsch 1996).

The consequence is that *the ocean is grossly undersampled in both space and time*. However this situation is improving rapidly, both due to remote sensing of surface properties, and intensive observational programmes since the 1990s, associated with the World Ocean Circulation Experiment (WOCE).

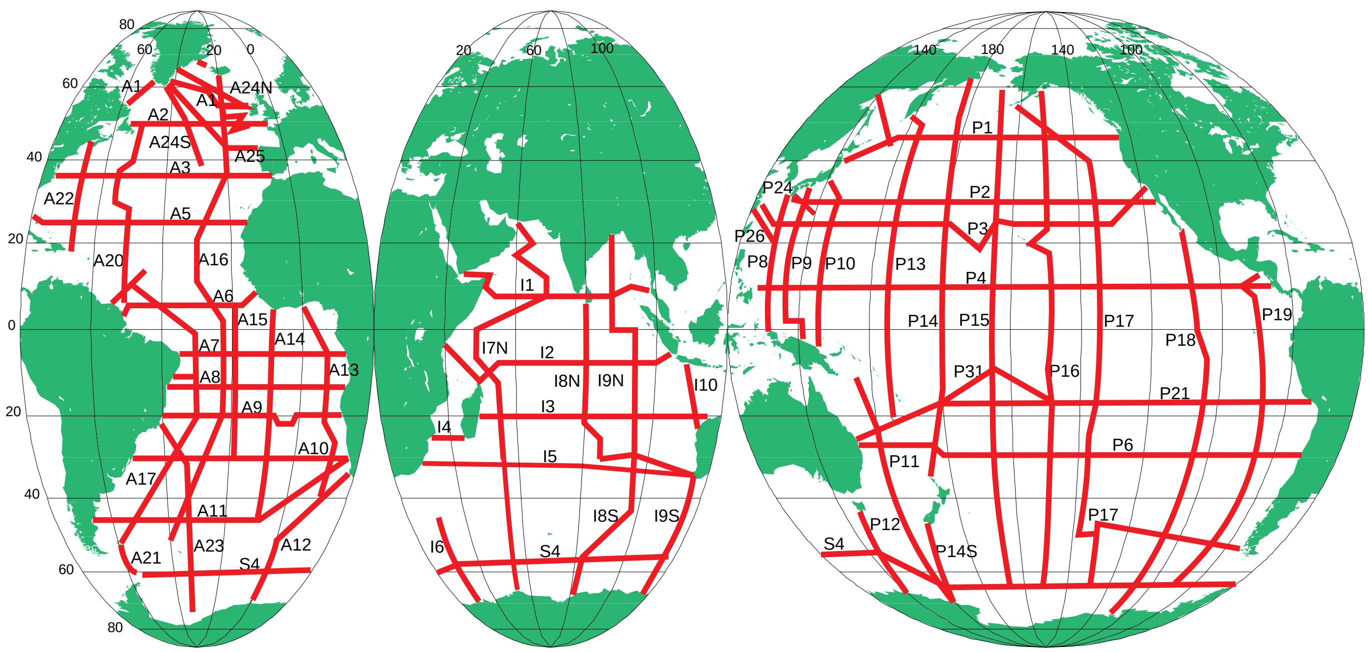
Approaches:

- *In-situ current meters*
- *Acoustic Doppler Current Profilers (ADCP)*
- *Hydrographic measurements*

  Measure $T$ and $S$ ($\Rightarrow \rho$) along hydrographic sections, and use thermal wind balance,

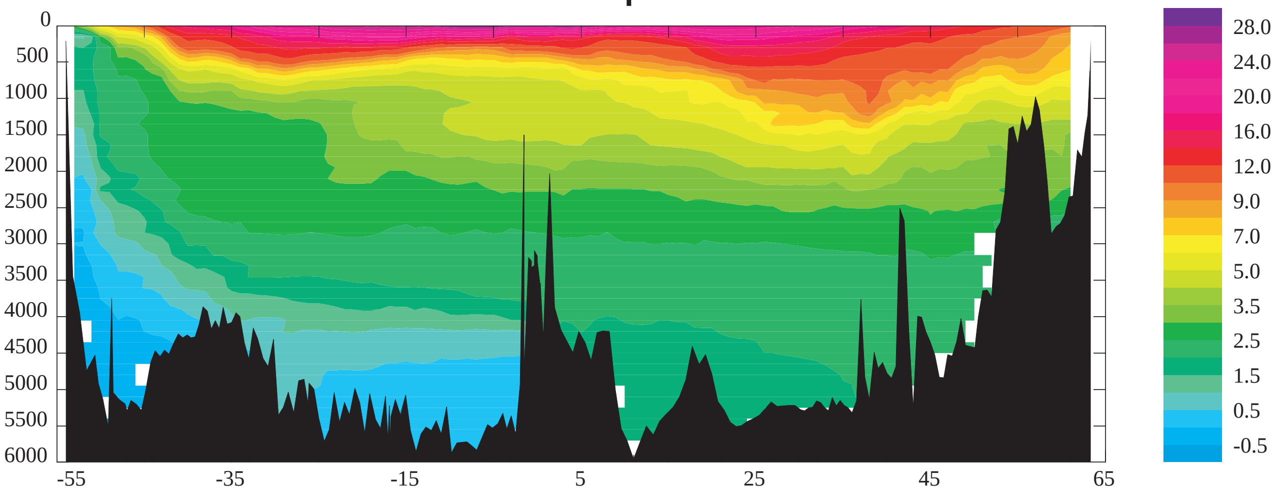
$$\frac{\partial u}{\partial z} = \frac{g}{\rho_0 f}\frac{\partial \rho}{\partial y}, \quad \frac{\partial v}{\partial z} = -\frac{g}{\rho_0 f}\frac{\partial \rho}{\partial x}, \tag{1.3}$$

  to infer geostrophic flow field subject to an assumed level of no motion.

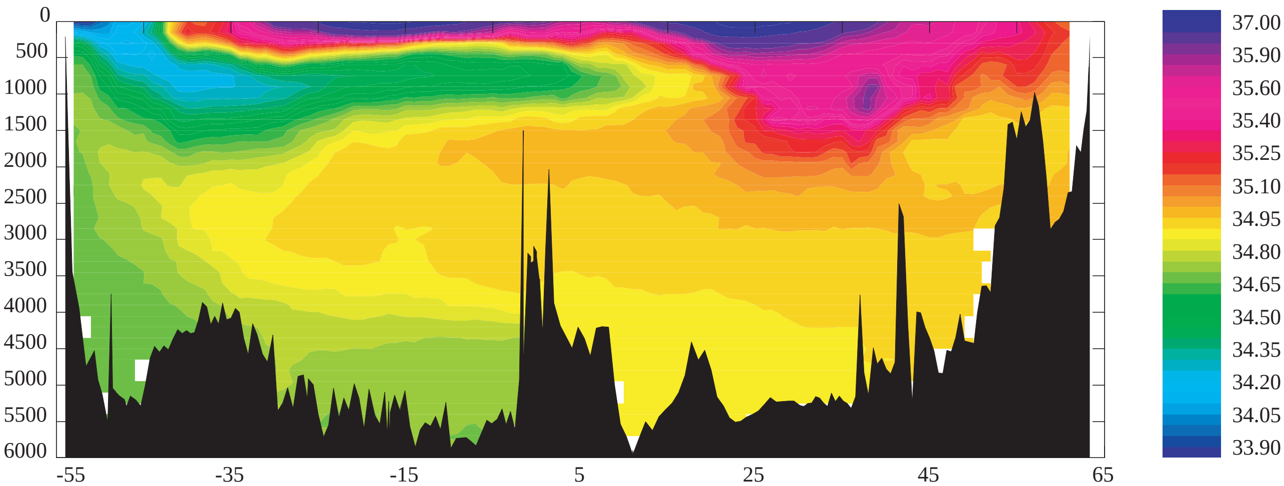



**WOCE Hydrographic Programme One-Time Survey**
**(Penny Holliday, WOCE IPO)**

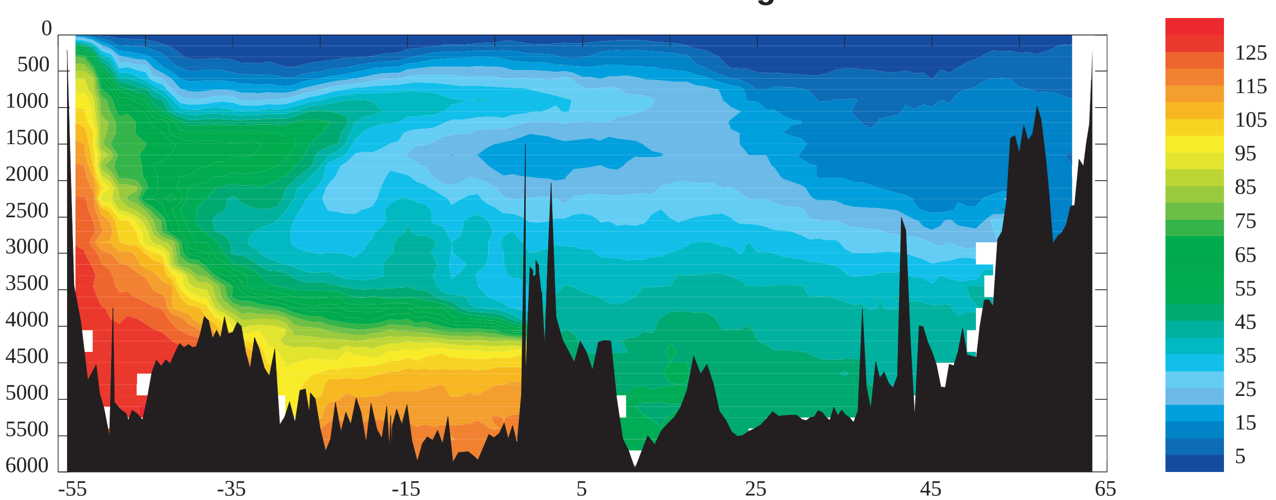
A16 Potential Temperature °C




A16 Salinity




A16 Silicate umol/kg




A16 - a WOCE mid Atlantic transect from south (left) to north.

(WOCE IPO)

- *Profiling floats (ARGO)*
  Track the flow at constant pressure (depth) or density; also take profiles of $T$ and $S$ as they surface ⇒ flow at reference depth and vertical shear from thermal wind balance.

- *Tracers*
  Dynamic (e.g., potential temperature, salinity)
  or passive (e.g., CFCs)

- *Satellite altimetry*
  Measure shape of sea surface from space ⇒ surface geostrophic circulation.

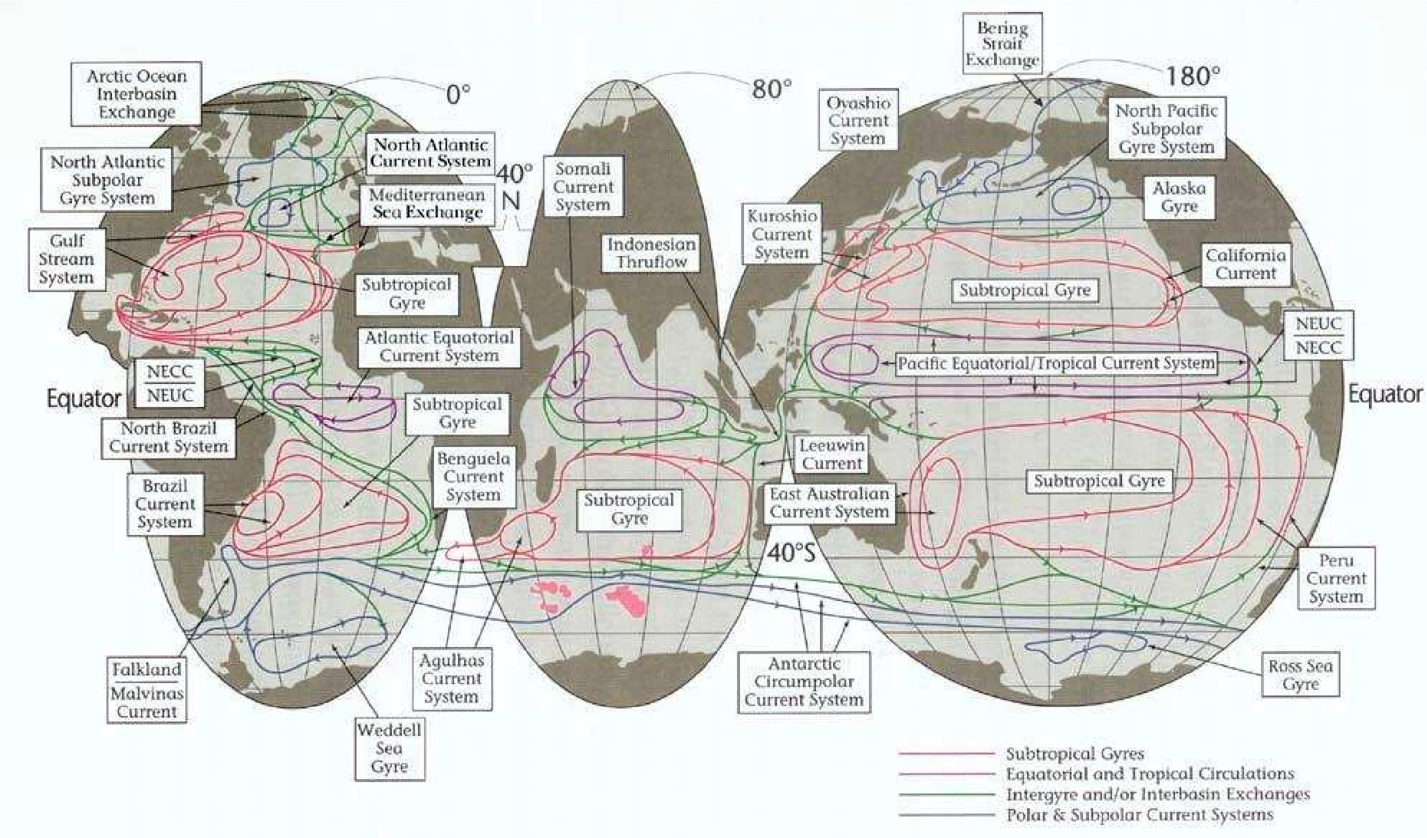
$$u = -\frac{g}{f}\frac{\partial \eta}{\partial y}, \quad v = \frac{g}{f}\frac{\partial \eta}{\partial x}, \tag{1.4}$$

  JASON/TOPEX-POSEIDON: global data every 10 days, 150km cross-track resolution at equator.
  (Poor knowledge of geoid an issue for time-mean circulation.)

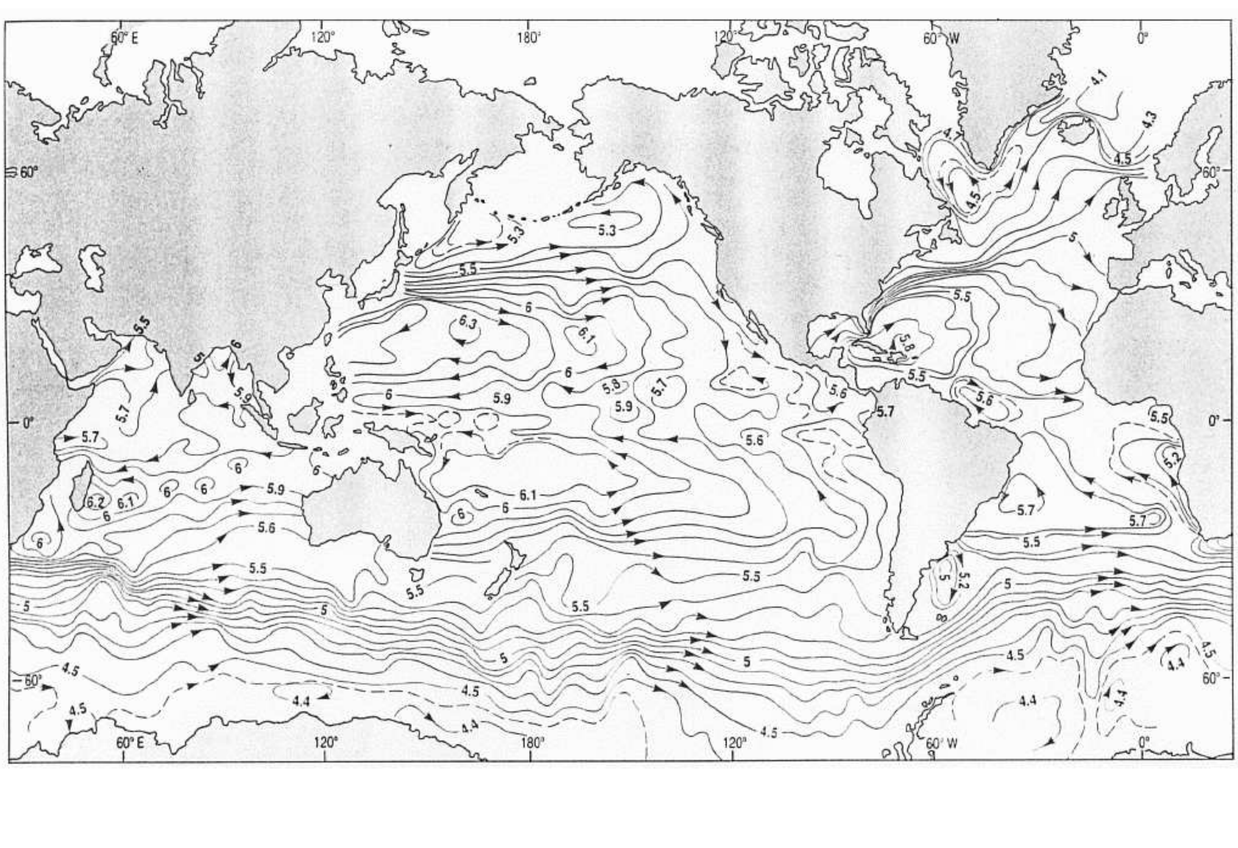
- *Acoustic tomography*
  Transit time of sound waves ⇒ mean temperature.

# OVERVIEW OF LARGE-SCALE CIRCULATION

Cartoon from Schmitz (1996):




Surface geostrophic streamlines assuming no flow at 1.5 km:

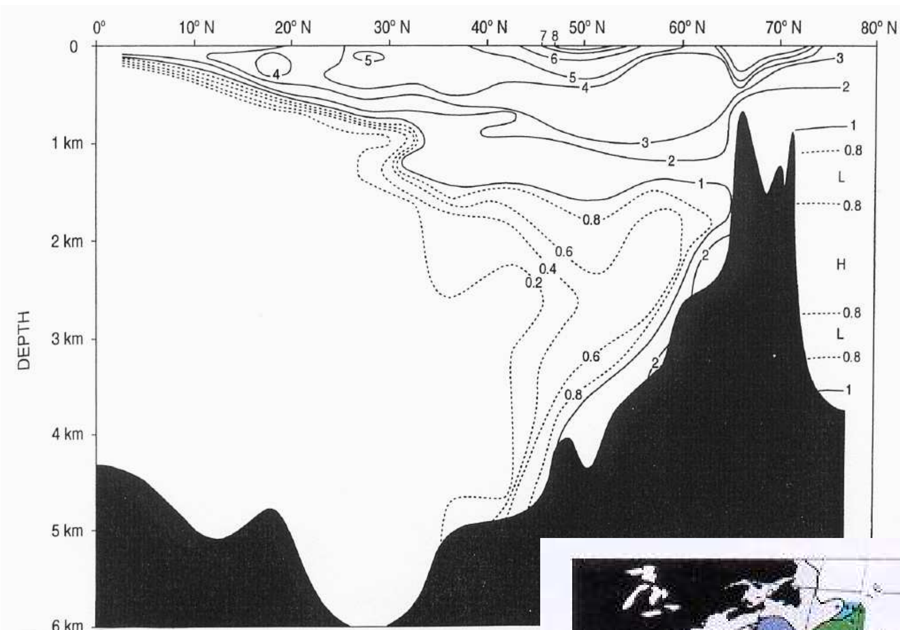


Main features:

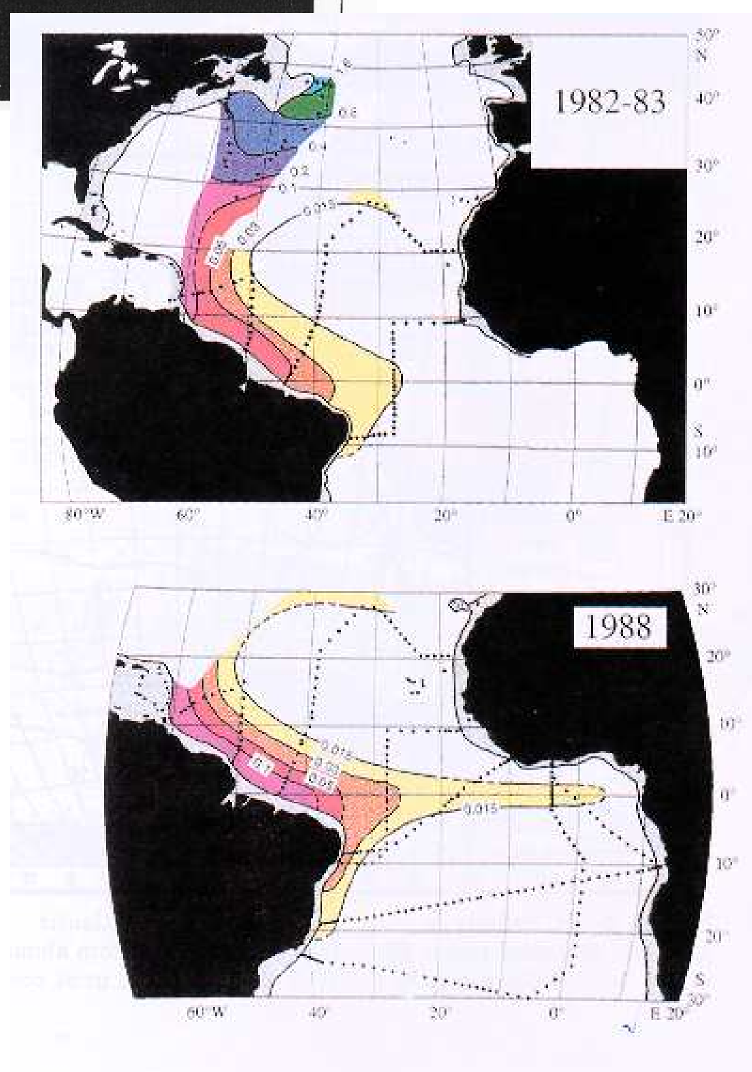
- *Subtropical gyres* in all major basins;
  anticyclonic,
  typical transports $T \sim 30\,\mathrm{Sv}$ ($1\,\mathrm{Sv} \equiv 10^6\mathrm{m}^3\,\mathrm{s}^{-1}$)
  typical velocities $U \sim 1\,\mathrm{cm\,s}^{-1}$.
- *Subpolar gyres* in northern hemisphere basins;
  cyclonic.
- Gyres closed by intense *western boundary currents*—e.g., Gulf Stream, Kuroshio;
  $L \sim 50\,\mathrm{km}$, $U \sim 1\,\mathrm{m\,s}^{-1}$.
  Transports can be enhanced by local recirculations, e.g., Gulf Stream transport $\sim 85\,\mathrm{Sv}$ at Cape Hatteras, and $\sim 150\,\mathrm{Sv}$ after separation.
- *Antarctic Circumpolar Current* (ACC) in Southern Ocean; $T \sim 130 - 200\,\mathrm{Sv}$, c.f. atmospheric jet.
- *Equatorial jets*.

- *Deep Western Boundary Current* in the Atlantic, southward transport $\sim 15 - 20\,\mathrm{Sv}$.

  N. Atlantic Tritium in 1971 (Östlund and Rooth 1990):

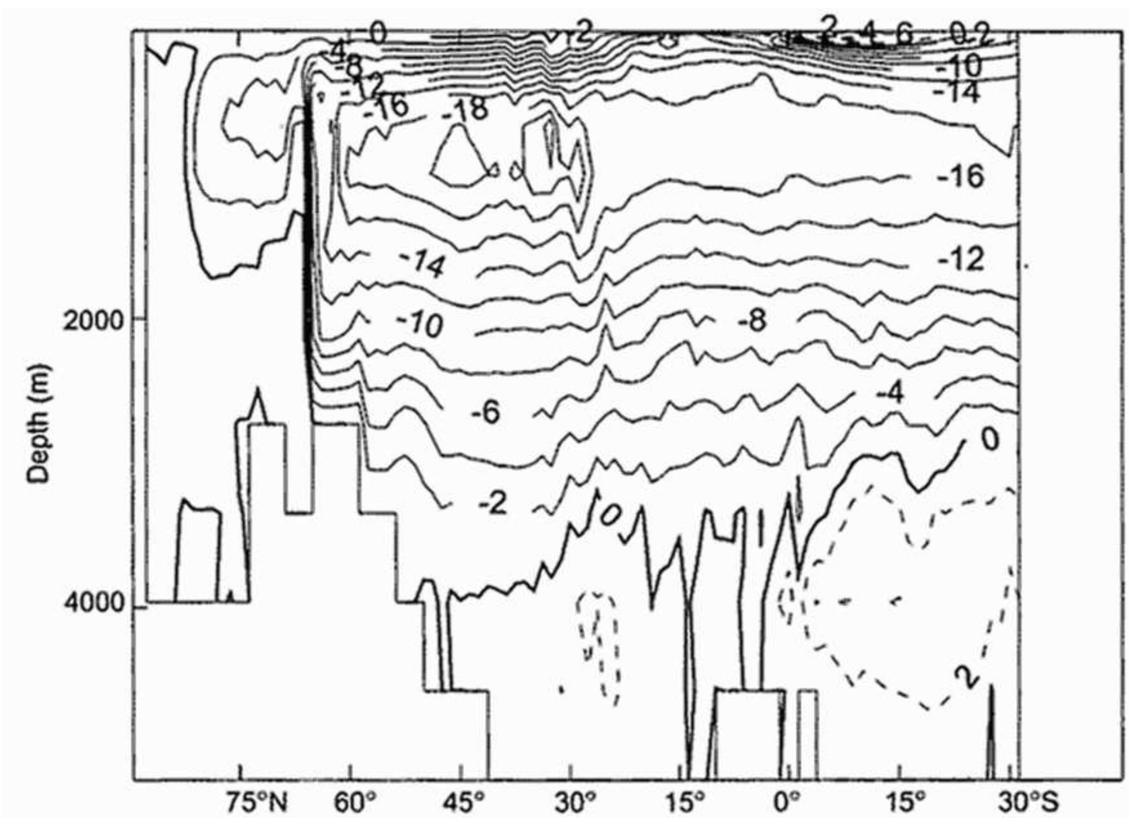



CFC-11 on $\sigma_{1.5} = 34.63$
($\sim 1.5 - 2\,\mathrm{km}$ depth)
(from Weiss et al.,
1985, 1993):

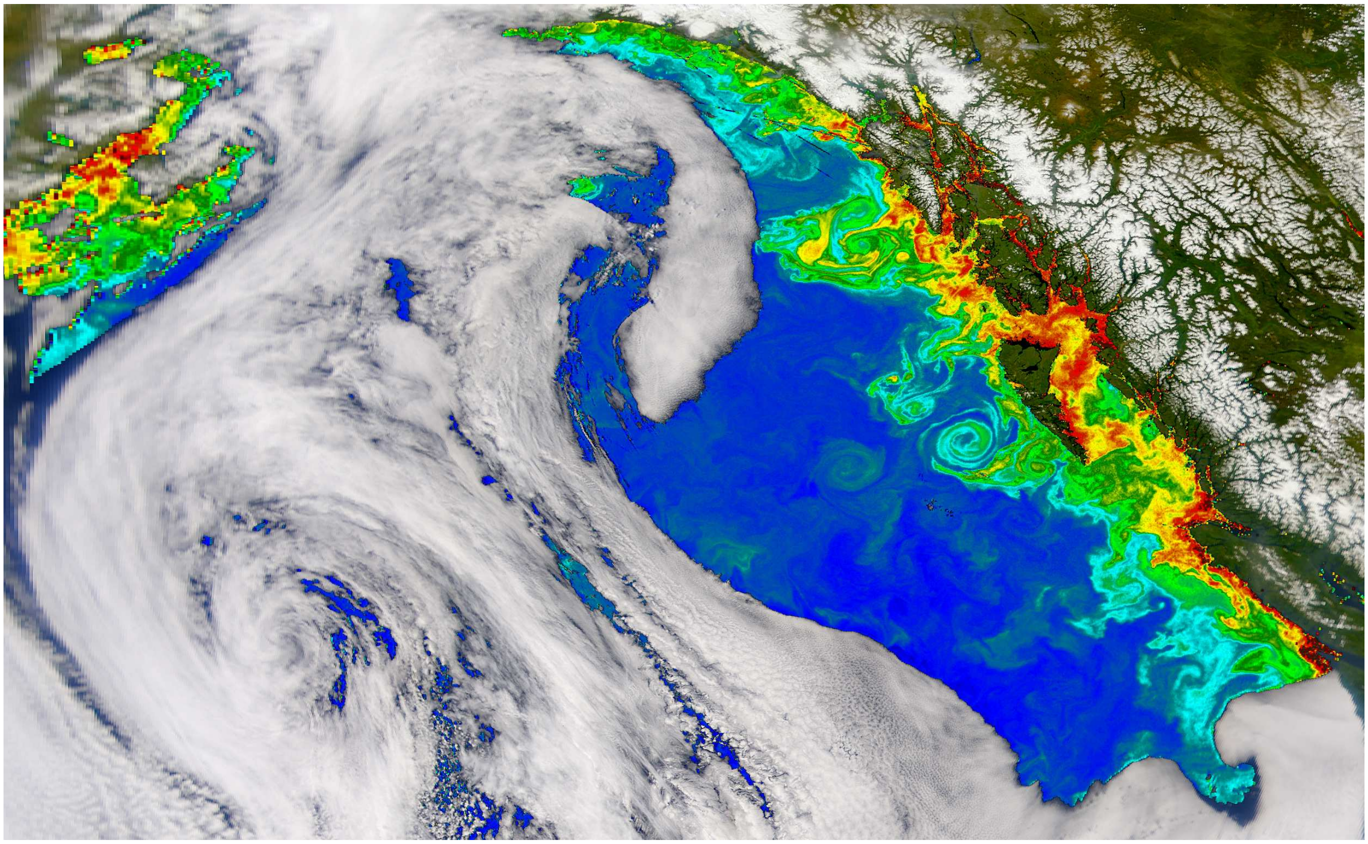


The Deep Western Boundary Current is part of an overturning circulation known as the *thermohaline conveyorbelt*.

For example, the net meridional overturning in the Atlantic (Sv) in the Atlantic from the Hadley Centre climate model HadCM3 (from Siedler et al. 2001):

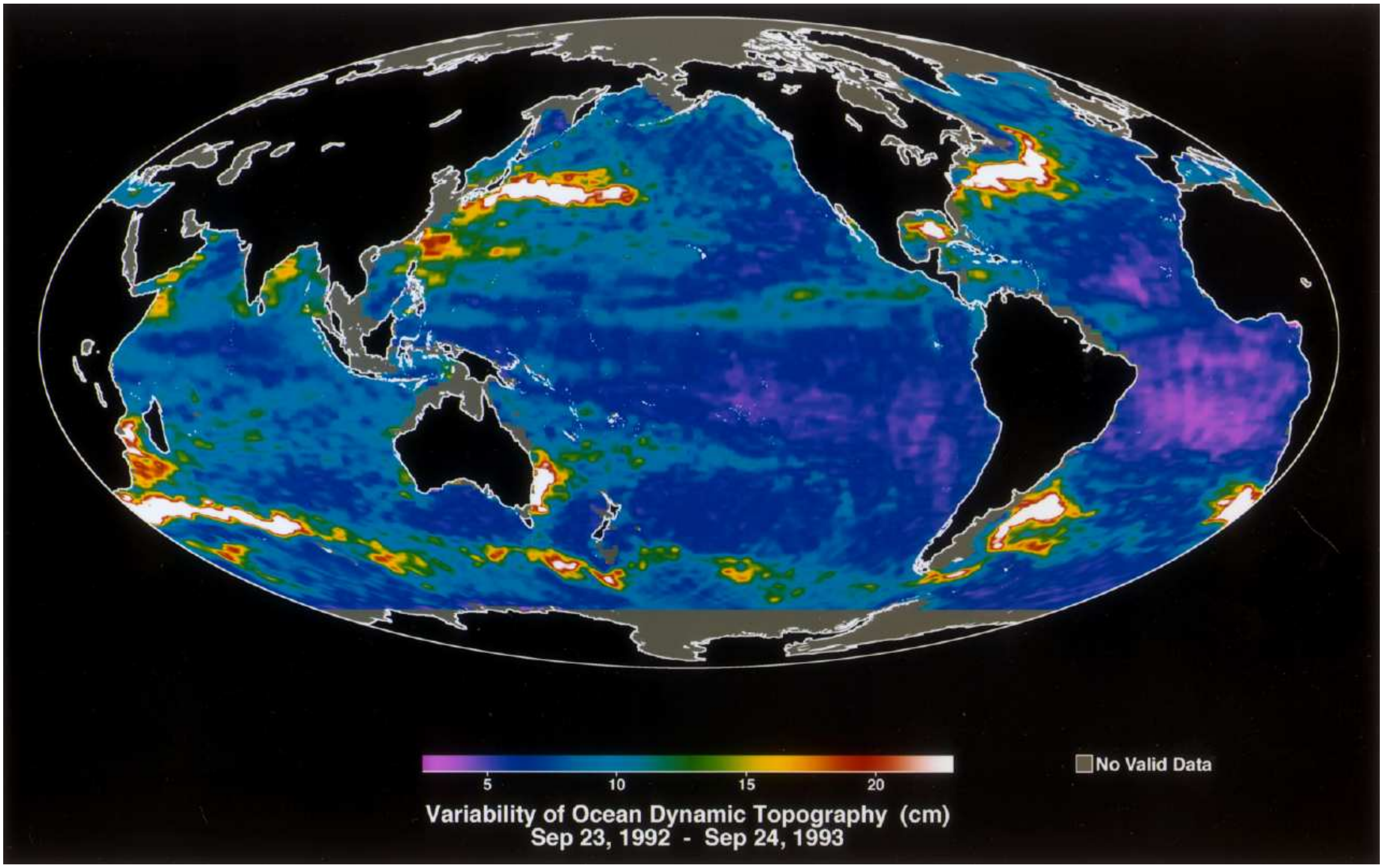


Superimposed on the mean circulation is an intense *transient eddy field*, with a dominant energy-containing scale of order 100 km — the analogue of weather systems in the atmosphere.



*Composite satellite image showing atmospheric cloud cover and a proxy for surface biological activity.*

Sea surface height variability from TOPEX-POSIEDON altimeter (http://topex-www.jpl.nasa.gov):



# SUMMARY OF KEY POINTS

- The oceans provides a significant poleward heat transport.
- Air-sea fluxes remain highly uncertain.
- Large-scale surface circulation dominated by subtropical gyres and western boundary currents, and ACC in the Southern Ocean.
- Thermohaline conveyorbelt carries about 1 PW of heat northward in the North Atlantic and may warm western Europe by several degrees.
- Superimposed on the “mean” circulation is an intense, small-scale eddy field ⇒ major challenges for observing and modelling the ocean.

# POSTSCRIPT: DIFFERENT VIEWS OF THE OCEAN

Wunsch (2001) suggests that the oceanographic literature suffers from a kind of multiple personality disorder:

- *The descriptive oceanographers' classical ocean*

  large-scale, steady, laminar, aims to depict "the" global circulation

- *The analytical theorists' ocean*

  quasi-steady, branch of GFD, aims to use simple models to deepen understanding

- *The observers' highly variable ocean*

  high temporal and spatial variability, regional focus

- *The high-resolution numerical modellers' ocean*

  relative newcomer, some elements of each of above, but differs from all of them

"Little communication between the apostles of these different personalities appears to exist; nearly disjoint literatures continue to flourish."

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*General reading*

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